Final Report
Prepared for US DoT
Contract Number: **DTPH56-13-T-000006**

Development, Field Testing and Commercialization of a Crack and Mechanical Damage Sensor for Unpiggable Natural Gas Transmission Pipelines

NYSEARCH / Northeast Gas Association

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May 2016

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Introduction

The 2002 Office of Pipeline Safety (OPS) regulations that require the inspection of all transmission pipelines, including those that are now deemed “unpiggable”, triggered the search for technologies that would make the inspection of unpiggable pipelines possible. In most cases, since the cost of modifying unpiggable pipelines is prohibitive, Direct Assessment methods and Hydrotesting were at that time the only technologies available for assessment. While contributing to the overall effort to characterize the pipeline networks, these technologies are expensive and cannot provide industry with the comprehensive information provided by in-line inspection tools, which is preferred among operators.

In 2001, NYSEARCH initiated and led an effort to develop ILI technologies for unpiggable pipelines. Following a feasibility study that proved the potential of robotics and sensory technologies to meet the system requirements and the many challenges of unpiggable lines, a development effort was started in 2004 with cofunding from NYSEARCH, PHMSA/DoT, NETL/DoE and OTD to develop the necessary tools. The Explorer family of robotics systems resulted from this effort. These are robotic platforms able to travel on their own battery power through unpiggable pipelines. They communicate with the operator through wireless communication and carry sensors for the non-destructive evaluation of pipelines. Six robotic platforms, i.e. the Explorer 6 (i.e. for pipe sizes of 6” carrying a Remote Field Eddy Current sensor and currently being redesigned to carry a Magnetic Flux Leakage sensor), Explorer 8 (i.e. for pipe sizes of 8” carrying a Magnetic Flux Leakage sensor), Explorer 10/14 (i.e. for pipe sizes of 10”-14” carrying a Magnetic Flux Leakage sensor), Explorer 16/18 (i.e. for pipe sizes of 16”-18” carrying a Magnetic Flux Leakage sensor), Explorer 20/26 (i.e. for pipe sizes of 20”-26” carrying a Magnetic Flux Leakage sensor; and also known during the R& D program as TIGRE; see Figure 1) and Explorer 30/36 (i.e. for pipe sizes of 30”-36” carrying a Magnetic Flux Leakage sensor) are commercially available providing the industry with unique capabilities for inspection of unpiggable pipelines.

Figure 1: Explorer 20-26

In addition, auxiliary equipment has been developed to support the commercial deployment of these tools. These include launching platforms for the launching, operation and retrieval of these robots under live operating conditions, in-line charging systems for recharging the batteries of these robots inside the pipeline, rescue tools for addressing the rare case of incapacitated robots from inside the pipelines without having to purge the pipeline and take it out of customer service.

The sensing capability that was originally developed for the Explorer series of robotic devices was tailored to detect corrosion damage, the primary source of damage to pipelines. However, there is a need to develop additional technologies to detect other sources of damage, namely mechanical damage and cracks, especially after some major incidents that took place the last few years, such as the San Bruno incident in California. As a result, in early 2011, NYSEARCH initiated a feasibility study to develop a mechanical damage and a crack sensor for integration into the Explorer family of robots, focusing on the implementation of the first system on the Explorer 20/26 platform. Following the positive results of that study, in September 2011, NYSEARCH approved a Phase II focused on building a crack detection sensor and a mechanical damage detection sensor to be integrated onto Explorer. The sensors were designed and tested in the laboratory. Following this effort, the present program was initiated that focused on completing the development of these sensors and their testing in natural gas pipelines prior to their commercial deployment. This report presents the results of this program which was successfully completed with the commercialization of these sensors through Pipetel Technologies, the company that has already established an excellent record in commercializing the Explorer family of robotic devices.

Technology Background

As mentioned earlier, in the last few years a number of high profile pipeline incidents have occurred that have fueled public interest and have renewed great interest in crack detection technologies as well as mechanical damage profilers. It is thus imperative that the Explorer family of platforms is equipped with state-of-the-art sensing technologies in order to be able to provide such capabilities. Already capable of metal loss detection, these additional sensing technologies would bring unpiggable pipelines the type of integrity assessment normally associated with standard inline inspections.

The mechanical damage sensor uses a laser profiler to identify the perimeter of the pipe and determine how round it is. The system consists of a laser projection onto the wall of the pipe and a video recording of the laser-illuminated pipe wall as the tool passes through the pipe. Deflection of the laser light in view of the camera can be used to measure the geometrical characteristics of the pipe wall.

New sensors have been developed for detecting and subsequently sizing cracks and crack-like anomalies in pipelines. Some of the technologies include transverse magnetic flux leakage (TMFL), ultrasonic, and EMAT (Electro Magnetic Acoustic Transducer). The crack sensor prototype under development for the Explorer 20/26 platform is a module that is added to the current tool. IE has demonstrated the use of transverse magnetic flux leakage (TMFL) technology to detect cracks in welds and has shown that such detection capabilities can be improved through the use of complementary sensors such as electromagnetic acoustic transducers (EMATs). Testing shows that both TMFL and EMAT sensors will be sensitive to ride conditions in the pipe.

Upon the successful completion of the project it is anticipated that these two sensors will be scaled for incorporation in the other robots that form the entire family of the Explorer platforms (6” to 36” range). The following sections describe the mechanical damage sensor, EMAT and TMFL systems in more detail.

Mechanical Damage Sensor

Mechanical damage sensors on inline inspection tools (smart pigs) typically consist of mechanical arms that ride along the pipe wall. When the arms hit a dent, their end against the wall gets displaced and the angle of the arm changes. This angle is monitored and the profile of the wall is established for the entire length of the pipe. For full coverage, these arms are arrayed around a central body, usually contacting the wall every 1in or less. For robotic devices for the inspection of unpiggable pipelines, like Explorer, arrayed modules are not attractive since they are large in size, consume substantial amounts of power and they will need to be collapsed to pass through miter bends and plug valves. An alternative approach to measuring dents was needed and an optical profiler was chosen as a result a feasibility study prior to this project. The profiler consists of a laser beam projecting on the pipe wall, combined with an offset camera. If the offset camera is viewing the projection, height deviations on the projected surface will be recognizable in the video. The advantage of this approach is that both the laser source and the camera can be located on the body of the camera module of Explorer, without the need for complex manipulation.

The components needed to implement this sensor on the Explorer platform are the laser ring that covers the surface of the pipe, a number of laser dots to properly position the camera, and three cameras offset further back from the laser ring.

Transverse Magnetic Flux Leakage Sensor (TMFL)

Existing sensors on the Explorer robots can determine the metal losses on the pipe due to corrosion. These are Magnetic Flux Leakage (MFL) sensors that magnetize the pipe wall in the axial direction thus providing excellent capabilities for corrosion defect detection. One of the areas with reduced sensitivity for this arrangement is axially aligned anomalies, such as cracks. By rotating the magnetization 90 degrees as shown in
Figure , also known as transverse magnetic flux leakage (TMFL), detection of axially aligned cracks can be achieved.

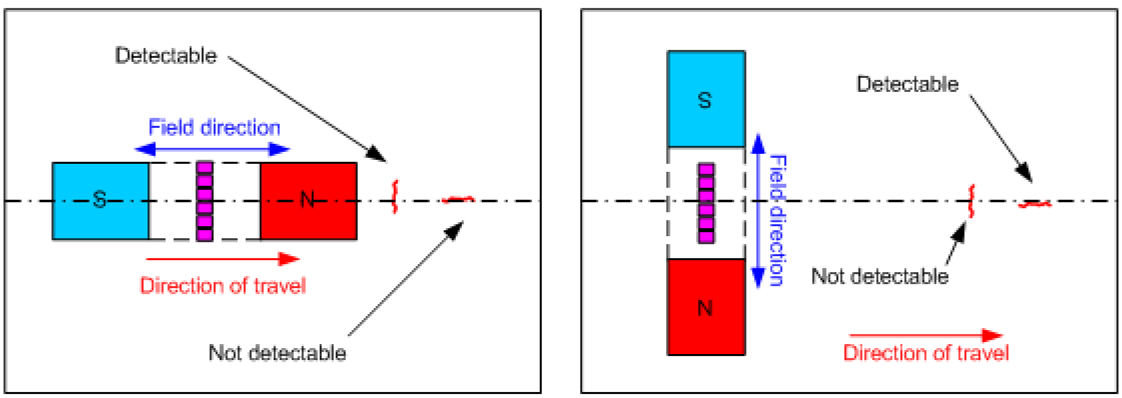

Figure 2: Rotation of the magnetic field to detect axially oriented features

Experimental data shown in

Figure 3 illustrates the detectability of a crack using a circumferential field. The north (red) and south (blue) poles are shown across a defect of 42% depth in a 0.250WT (Wall Thickness) plate. The color plot shown indicates the radial hall sensor reading in the vicinity of the crack, obtained by directly measuring the radial field vector along the surface of a plate. The crack signature can plainly be seen.

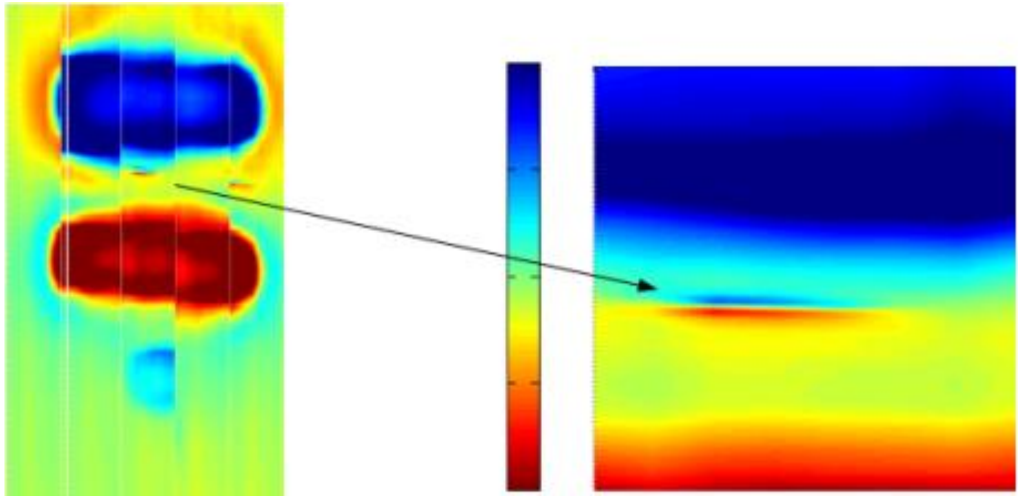

Figure 3: Detectable crack using a circumferential field

The preferred approach for a TMFL sensor integrated on Explorer is to achieve full coverage of the pipe circumference on the shortest module length possible. The crack sensor uses two sets of circumferential bars. There may be some reduction in field strength due to the proximity of the sensing sections to each other, but for crack detection this is acceptable. Tests similar to

Figure 3 show good detectability of cracks even in the region around the edge of the magnet poles.

ElectroMagnetic Acoustic Transducer (EMAT)

EMATs bring ultrasonic methods to applications where an acoustic couplant, usually a gel or water, between the transducer and the test article cannot be used. This is the case in gas pipelines where application of liquid on the interior of the pipe is not feasible. An EMAT sensory system requires a magnetic field in the base material, along with a pulsed coil that causes an acoustic pulse to travel through the material.

Implementing an EMAT sensor on Explorer involves establishing a suitable magnetic field for generation of the acoustic pulse that travels around the pipe circumference (see Figure 4). Within the magnetic field are coils (or windings) that are riding as close to the pipe wall as possible, which transmit and receive this electromagnetic pulse. These components and their corresponding electronics need to be packaged in a manner that is suitable for pipeline conditions. The physical components required for EMAT data acquisition are summarized as follows:

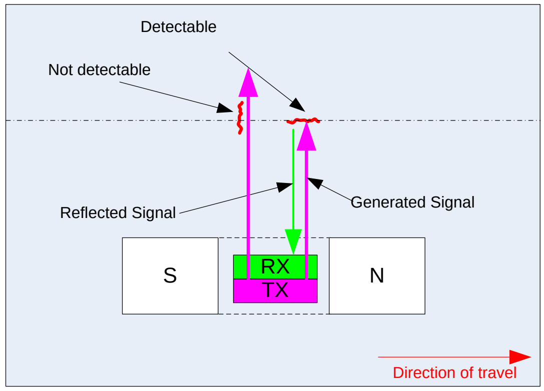

Figure 4: EMAT detection of cracks

1) Magnetic field: The magnetic field is required in conjunction with an electrical winding. The magnetic field is perpendicular to the direction of wave travel. An oblique angle can improve the magnitude of the signal.

2) Transmitter pulser and coil: A high voltage pulse is applied to the winding, which excites the pipe wall with an acoustic pulse. The high voltage pulse used in this system is in the range of 500 - 600 kHz, depending on the geometry of the coil. The pulse is high voltage (300V peaks) however, the overall duty cycle is low since this voltage is applied in bursts.

3) Receiver coil and signal processing: Magnetorestrictive forces directly underneath the winding generate electrical signals as they pass through the solid. The first pulse seen is a direct pulse, which is the pulse as it travels through the pipe directly to the receiver coil. Any response after the direct pulse is typically reflections off edges encountered in the pipe. These edges can be a seam weld, metal loss, or crack features. Data is stored on onboard flash memory for download later into data analysis software.

4) EMAT Controller: For multiple transmitters, which are required in order to increase the detection capabilities of the system, the pulses need to be ordered in such a way as to allow the pulse amplitude to attenuate before the next pulse is generated. If more than one pulses is traveling in the circumference at any given time, the reflection path will have multiple peaks in the received signal. Therefore, the pulses generated by multiple transmitters, and the receivers used to detect reflections, need to be scheduled accurately. This is performed by an EMAT controller, which provides synchronization and scheduling for all of the transmit/receive units around the pipe.

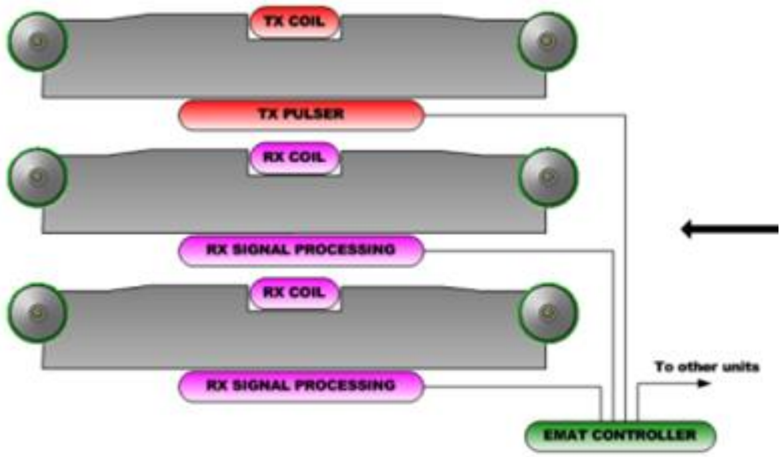

Figure 5: Layout of components for EMAT

The EMAT components, transmitters and receivers can be arrayed around the pipe circumference as shown in Figure 5

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System Design

Mechanical Damage Sensor

One of the deliverables of this project is the implementation and testing of the optical mechanical damage sensor aboard the Explorer tool. This sensor is situated entirely on the nose module of the tool. This location was chosen because it was most readily adaptable for this purpose and it provided the best view of the pipe wall from all sides.

The sensor system consists of three major sub-assemblies:

1) A laser ring mounted as far forward as possible on the nose that projects a uniform light line onto the pipe wall.

2) The cameras are assembled towards the rear of the nose. These cameras are oriented in such a way as to capture the arc of the line on the pipe wall as well as the reference dots which are mounted between the camera locations. The three cameras are located at 120deg angles around the nose circumference.

3) The electronics stack, which encodes and stores the video feed from each camera, and controls the focus, power and other settings on each camera unit.

The sensor implemented on the nose can be seen in Figure 6 with the laser line projected onto the pipe wall.

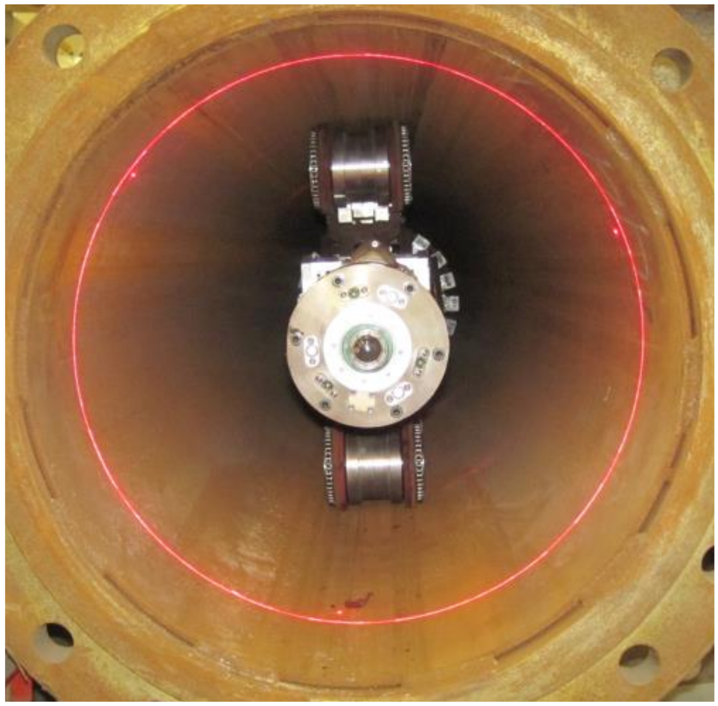

Figure 6: Mechanical damage sensor on Explorer nose

To verify the performance of the technique under the effects of external pressure, the components for the MDS were subjected to pressure tests to establish survivability and characterize the effect on the calibration for sizing purposes. These tests were carried out in InvoDane's laboratory using our pressure tank. This tank is capable of testing to pressures up to 2,000 psi while monitoring the performance of the equipment from outside.

InvoDane has created some basic tools for manipulating the camera video output so that dents, ovality and other variations in well radius can be viewed and quantified. These tools include:

- generation a full pipe view from three cameras,
- measurement of radius at any angle

Tests were conducted to determine the overall detectability of height of the system using various heights of blocks arrayed around the pipe circumference. The pictures in

Figure 7 were taken in a 20-in pipe with 0.250in wall thickness. A small block of varying height was placed across the laser ring and the picture was taken. For blocks even as small as 0.125in, the variation can be seen. For a 20in pipe this corresponds to 0.6% of the overall diameter, which is within the target value of 2%.

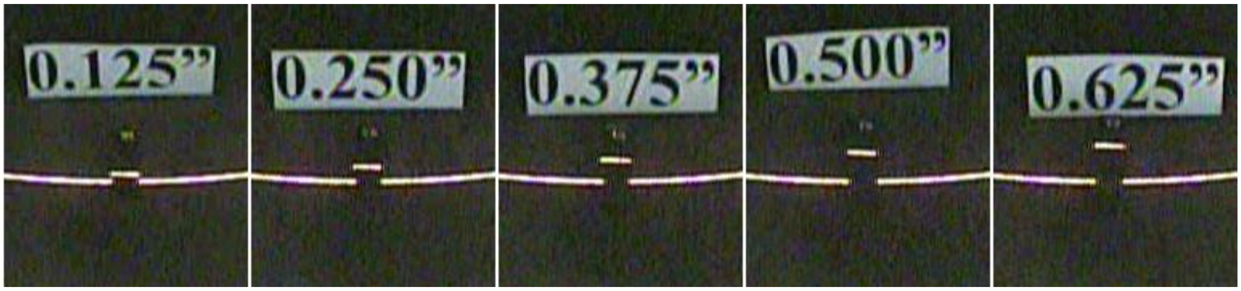

Figure 7: Sample view of deflection of the laser ring for different heights

The steps taken to analyze the data generated by the MDS are proprietary.

Calibration tests using known dents have been conducted for the Mechanical Damage Sensor (MDS). These have been carried out in three stages. First, the overall resolution of the system was tested using system components and known defects. These tests showed the sensitivity of the system to be 1/8-in in height. The axial resolution is 0.13-in and maximum circumferential resolution is 0.040-in. However, this has been down sampled to 0.250-in to limit the number of channels that are processed and match the total number of sensors used for MFL data.

The second stage was to determine the calibration coefficients through the use of a calibration block, while the last stage of the calibration evaluation for the MDS is to apply the sizing algorithms to pipes with dents of known heights. One dented pipe in InvoDane's pipe inventory is 22-in in diameter with 0.25-in wall thickness. The pipe has 9 dents at various locations in the pipe (see Figure 8) and is slightly oval in shape. The dents range in height from 0.9% to 2.9%. The pipe was scanned and the data can be seen in
Figure 9.

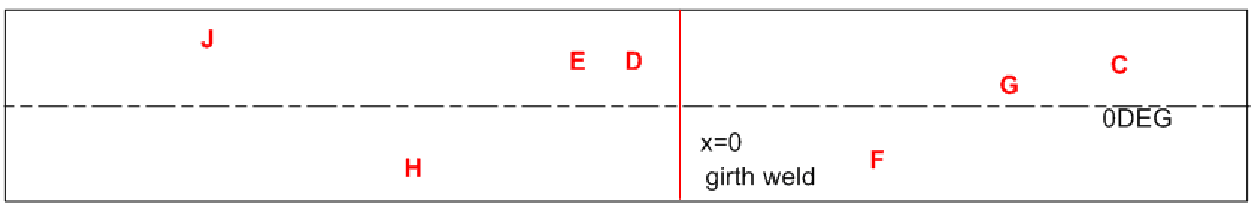

Figure 8: Locations of dents in 22-in pipe

All of the dents on the pipe are visible. Sizing estimates have confirmed 1-2 mm accuracy of dent sizing, which is consistent with the height specification.

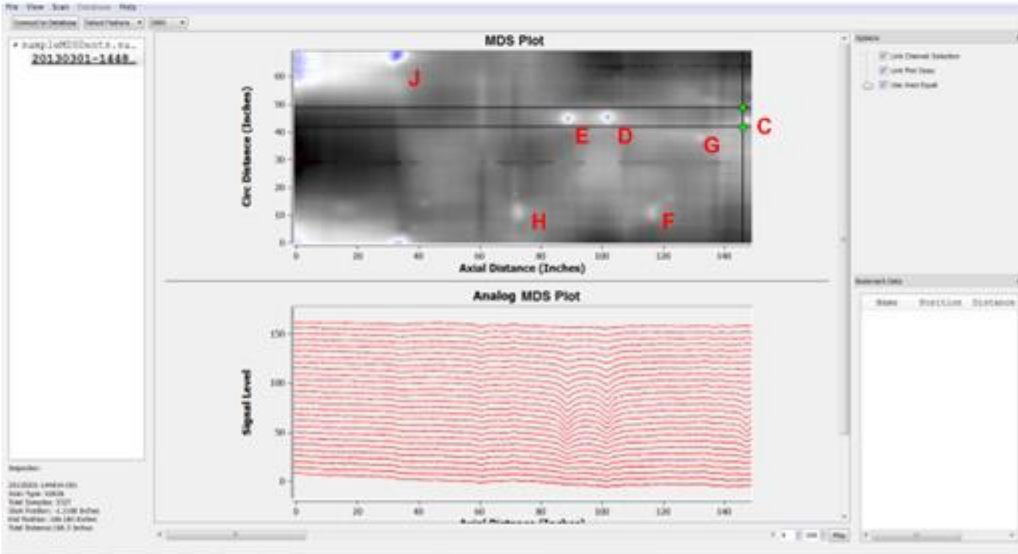

Figure 9: DataTel view of MDS data on 22in dent pipe

At the time of the writing of this report, the MDS system is fully integrated into Explorer platforms and performing commercial inspections. The MDS system consistently achieves dent measurement specifications of sub 1% accuracy and has been verified in client validation pipes. The MDS system is typically deployed on all commercial inspections and to date has identified, sized and reported 138 dents during the 2013 and 2014 inspection seasons. In addition to its use aboard Explorer 20/26, the MDS sensor has been used on 8in, 10/14in, 16/18, and 30/36 robots. The MDS (mechanical damage sensor) has been commercialized under the name Laser Deformation Sensor (LDS).

Crack Sensor

Two different technologies were combined in order to detect axially aligned cracks in unpiggable pipelines. These technologies were EMAT (Electro Magnetic Acoustic Transducer) and TMFL (Transverse Magnetic Flux Leakage).

The key aspect of the sensing section was the requirement for a full circumferential field around the pipe wall. This field required many design iterations and test setups. This proved to be a very challenging problem that was finally solved using an innovative solution that is proprietary.

The sensing section concept chosen has individual poles separated into sections. The sections allow for full coverage with MFL sensors. The magnets are turned on and off via a proprietary mechanism. The configuration chosen was required in order to reduce the tow force characteristics as well as increase the magnetic field strength in the pipe wall. The concept was demonstrated in experiments in the laboratory before completing the design. The magnetic flux was simulated using finite element analysis (FEA) in order to determine the region of suitable magnetic flux magnitude where the hall sensors will be located.

The EMAT sensors that are integrated on the crack sensor have three controllers, which handle transmission and sensing functions for the acoustic waves travelling in the pipe. The transmitter has a pulse control module and a pulse driver module. The pulse control module converts the 24V into a high voltage source as well as switches the control lines of the pulse driver module. The pulse driver module takes the source and control lines to drive the coil at the desired frequency and duty cycle. The EMAT receiver modules have a digital and analog portion which amplify, filter, and record the EMAT signal.

The poles can be retracted down to the minimum diameter of the robot so the sensor can be turned around corners in the pipe and into the hot tap used for launch and extraction. Before moving the poles, the magnets need to be turned off.

The steer module attached to each end of the crack sensor contain the support wheels which support the weight of the sensor during inspection. Because of this support method, the tow force of the crack sensor is further reduced to levels comparable to the conventional axial MFL system currently towed by Explorer.

All new components were individually pressure tested to 750 psig to ensure proper operation under live conditions in a pipeline.

Overall, the new crack sensing section consists of the following components:

- Collapsible magnetic pole sections that contact the pipe wall.
- Hall sensors are placed between the poles to measure magnetic flux leakage.
- EMAT transmitters and receivers
- The magnetic section is supported in the pipe with collapsible rollers at each end
- Customized steer modules pitch and rotate the crack sensor through the pipe

- The sensor is mounted to robot drive modules through standard auto-connection points at each end

The crack sensor analysis tools are used to organize the data for viewing and ultimately sizing anomalies identified in the data (see Figure 10). The data is collected and organized separately until it is viewed side by side in the viewing software (commercialized under the name DataTel). There are four main types of data collected by the robot during a scan with the crack sensor. First, navigation and robot configuration is recorded when the robot is in the pipeline. From this data, the analyst can determine the robot position and possibly other indications of defects such as markings on the inside of the pipe. Second, the robot collects MDS (Mechanical Damage Sensor) data using the laser ring on the robot. This process is described in the previous section. Third, the crack sensor collects TMFL data from elements arrayed around the pipe wall. This data is stored directly on the sensor elements and downloaded at the end of the inspection. Fourth, the EMAT data is collected and stored aboard the receivers arrayed around the pipe wall.

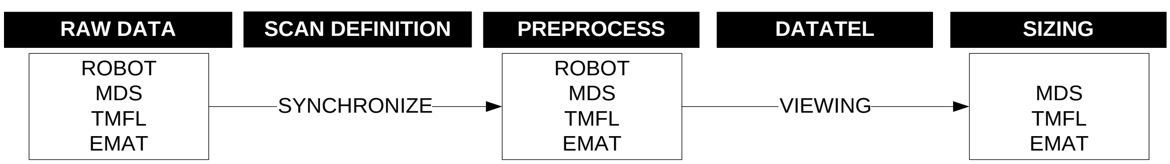

Figure 10: Crack sensor and MDS data handling

<u>Robot configuration</u>
Currently the entire configuration of the robot (throughout the robot) is recorded during a run. Along with battery level, power status, communication strength, etc., the position of the robot can be reconstructed after a run. This information is used to define a scan. Using this approach the raw data is broken up into segments for pre-processing. The scan definition includes a time and spatial synchronization step that aligns and maps all data to a particular location in the pipe.

<u>Traverse Magnetic Flux Leakage (TMFL)</u>
The TMFL data handling was integrated into the viewing software during the implementation process. The data handling of TMFL data is consistent with Axial MFL techniques. The hall sensor data is collected and stored in a similar way, the data is spatially sampled using the same scripts, and the resultant data files for input into DataTel are the same. DataTel has been modified slightly to differentiate between TMFL and axial MFL data using the robot configuration at startup.

The main effort moving forward with the TMFL sensor, once the sensor was build, was to calibrate the sensors and develop the sizing algorithms to determine how deep cracks are once they have been detected.

ElectroMagnetic Acoustic Transducer (EMAT)

The crack sensor collects EMAT data from receivers around the pipe wall responding to pulses generated by transceivers (pulsers). This data is stored aboard the EMAT receivers directly as samples. Each pulse generates one sample on each receiver. If sensor moves through the pipe and is sampled at discrete points, then the signals can be stacked up next to each other. The distance is plotted on the x-axis. A sample of this plot is shown in
Figure 11. A real time data view has been implemented for EMAT aboard Explorer to allow the operator to evaluate the quality of the signal during an inspection.

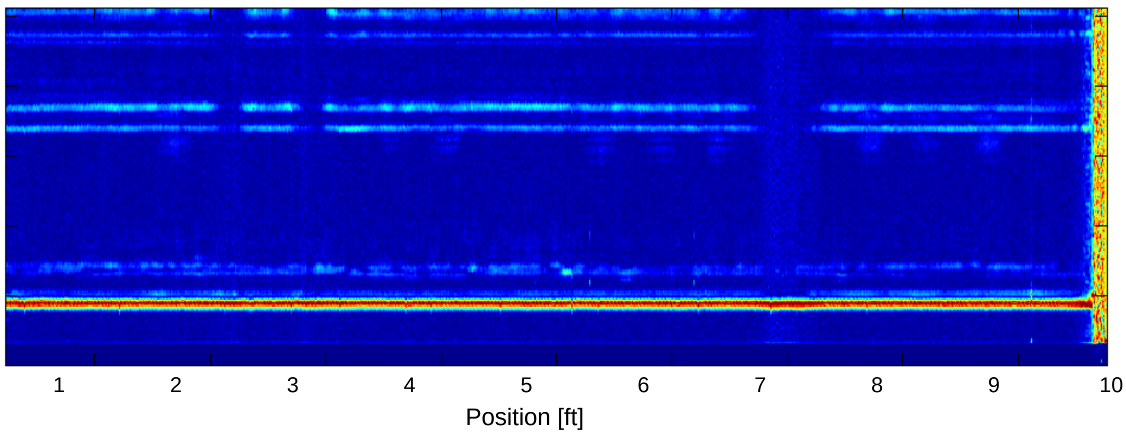

Figure 11: EMAT data visualization

Most of the above early work on the sensor design effort was carried out before the initiation of this phase of the work, but is presented here for completeness. However, final assembly and testing of the system, and improvements and optimization of the sensor were carried out as part of this work.

Team Project Activities

Task 1.1: Preparation for first live demonstration

An interim crack sensing section was implemented using magnet bars from the conventional sensing section. The objective was to implement the EMAT sensors aboard Explorer first, while the TMFL section was being assembled in order to gain understanding on the behavior of the system in pipeline conditions. EMAT sensors were mounted aboard a number of standard axial MFL magnet bars.

To determine the detectability of the system, the EMAT sensor was tested in a sample cracked pipe that was purchased to provide a measurement of cracks in a systematic way. The pipe, 10ft long, has 24 flaws in it, in the base material and in a seam weld. All of the flaws are 1in long and of various depths. The pipe defects are shown in Figure 12 and Figure 13. On one side of the pipe are flaws in the base material and on the other side there are crack defects in the weld. These are actual cracks build on the pipe, using a proprietary process owned by the company that manufactured them for us, and not machined defects.

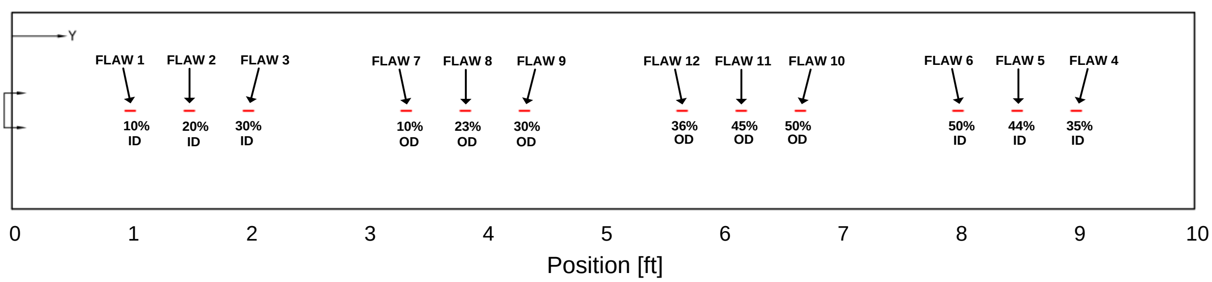

Figure 12: Crack defect pipe - base material side

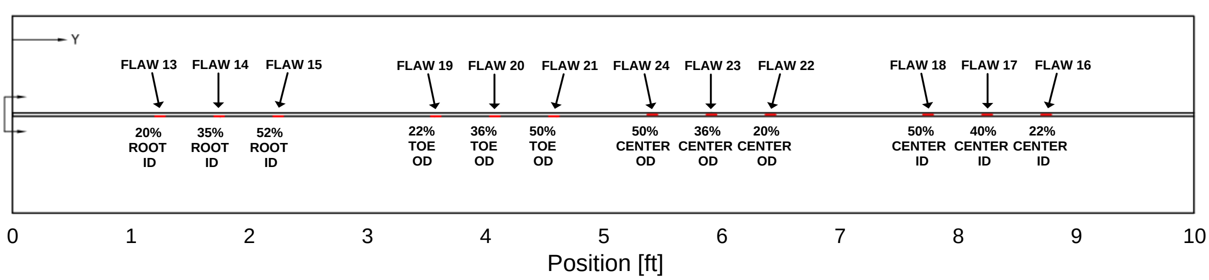

Figure 13: Crack defect pipe - seam weld side

The EMAT sensor was tested on the pipe with the cracks. The data was sampled and stored aboard each RX unit and then downloaded off the robot along with other robot telemetry. By combining the odometer and crack sensor data files, the data analyst can create plots as shown in Figures 14 and 15.

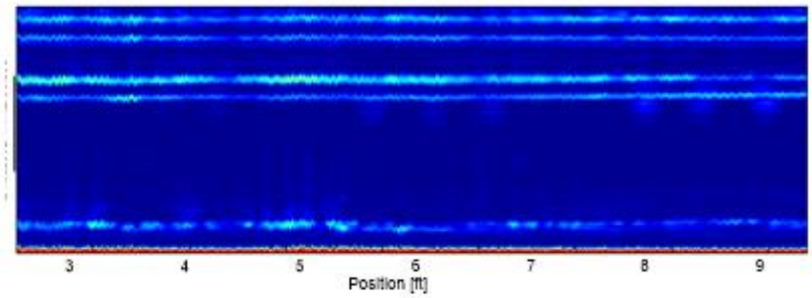

Figure 1 and 15 are a color plot of the signal magnitude along the pipe. This signal should be consistent throughout the scan. Deviations in the magnitude of this line indicate liftoff of either the transmitter or receiver, or changes to the signal magnitude due to pipe characteristics. The reflections from the crack defects in the pipe can be seen right beside the direct pulse signal.

For base material cracks the largest response are on the ID of the pipe between 8 and 9 ft for cracks with depth between 35% and 50% of wall thickness. OD cracks with depth of 30%-50% of wall thickness can be seen plainly between 4 and 7 ft.

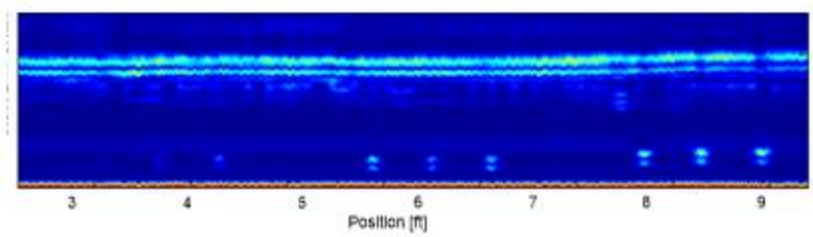

Figure 14: Crack defect pipe scan with EMAT- base material cracks

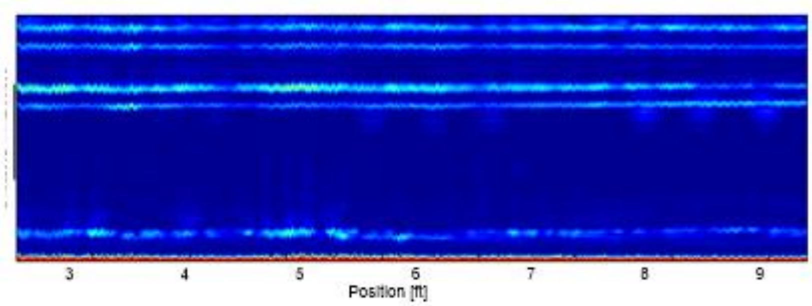

Figure 15: Crack defect pipe scan with EMAT- seam weld cracks

For the TMFL sensor, after assembly, the system was tested to ensure proper data collection was achieved:

- Ride quality was analyzed and revised in order to improve the engagement of the sensors with the pipe wall.
- The system was tested in a vertical launch setup to ascertain how the robot would respond to the weight and length of the system. Adjustments to the launch and receive scripts were made as a result. The test showed that up to 20% more force would be needed just to pull the robot out of the pipe.
- The system was pulled through the crack defect test pipe to determine overall detectability by the TMFL sensors.

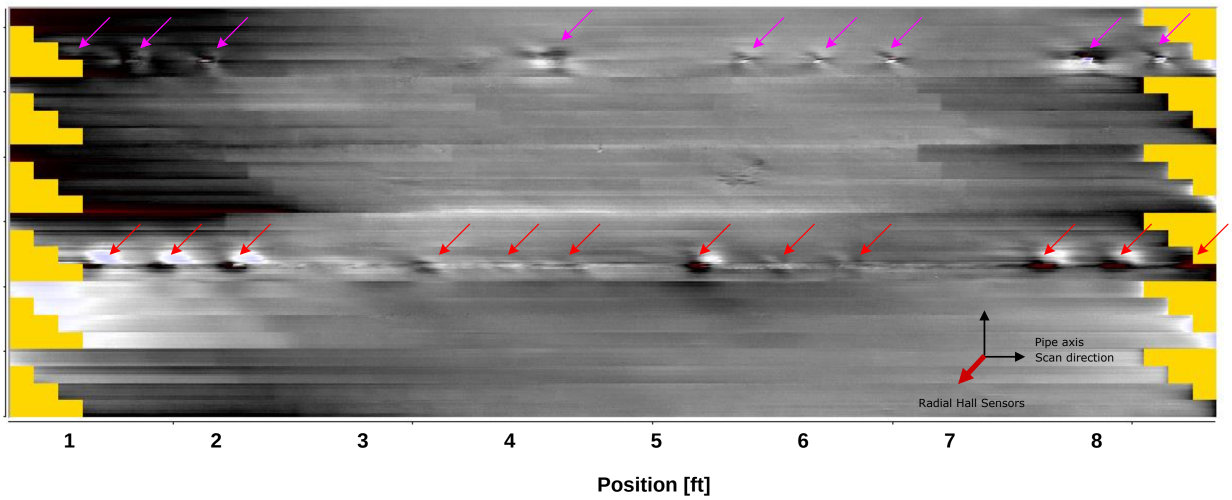

Figure 16: Crack defect pipe scan with TMFL sensors

Data from the scan is shown in Figure 16 and shows exceptional data quality for both the seam weld and the base material defects. The only defects that were not detected by the scan were the small OD cracks of depth equal to 10% and 23% of wall thickness.

The EMAT sensors were also tested in a similar way aboard the now assembled crack sensor. Data from the EMAT sensors installed aboard the TMFL section indicate results consistent with the interim EMAT sensing section.

The data analysis for the TMFL has been implemented into viewing software while the EMAT data analysis is still viewed using MATLAB.

In the meantime, NYSEARCH staff worked with representatives of a member company in NYS, and funder of this project, to secure a pipe for the first field testing of the sensor. The planning process involved identifying the pipe in which to test the sensor and planning all logistics to the last detail to make the demonstration a success. Planning was completed on time successfully.

Task 1.2: First live demonstration

Testing the integrated crack sensor aboard Explorer was performed in two phases: operational testing and field testing. First, the system was tested in a pipe similar to those found in the field. There were two operational tests performed. The first location was a segment of a pipeline that had recently been in service. The goal of this test was to provide baseline signal feedback for the EMAT system design cycle and help finalize the overall sensor configuration. InvoDane installed and tested a developmental version of the EMAT sensing technology to this location on May 28, 2014.

The pipeline provided for testing by NYSEARCH (see Figure 17) was owned by a NYS utility and was carried out on location. It had been removed from the ground intact. It had been removed due to suspected integrity issues in two girth welds located at the end of the segment. The segment was over 150 ft long with girth welds every 20 ft. The pipe was installed in 1951 and was 22.5 in in diameter with a wall thickness of 0.25 in. The pipe was cleaned prior to testing.

Figure 17: 22.5" OD, 0.25" WT pipeline segment

Figure 18: Coal tar coating partially removed from pipeline segment.

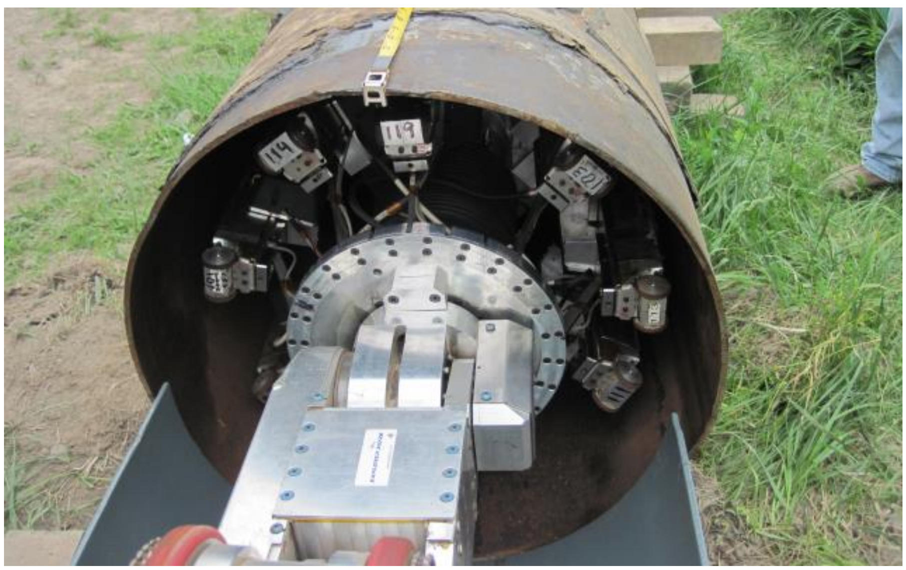

Figure 19: EMAT sensor entering test pipe

The original coal tar coating on the outside of the pipe had been removed in some areas in order to evaluate the condition of the pipe due to integrity concerns at each end of the pipe (

Figure 18). Furthermore in preparation for the test, NYSEARCH removed the coating on some of the pipe including a 60 ft segment in the middle of the pipe. This was done in order to test the sensor for both cases of a coated and non-coated pipeline.

Four scans in total were performed through the pipe (see Figure 19). Only scans three and four are shown below. Scan 3 was performed by pulling the sensors off the pipe wall and over the girth weld. Scan 4 dragged the EMAT sensors directly over top of the girth weld. The data is represented in Figure 20 and Figure 21 with signal travel time as the y-axis and sensor axial position as the x axis.

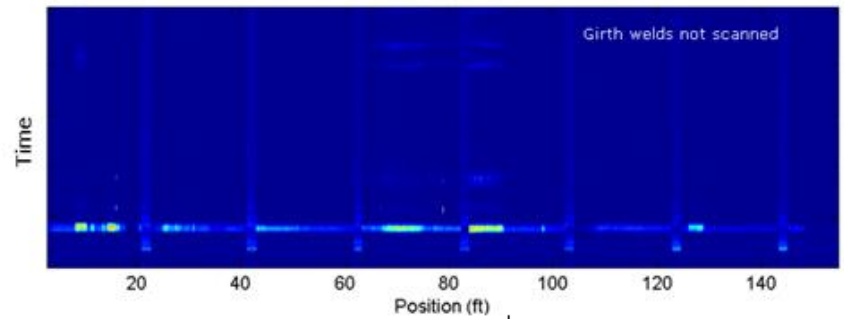

Figure 20: EMAT data, sensor lifted over girth welds

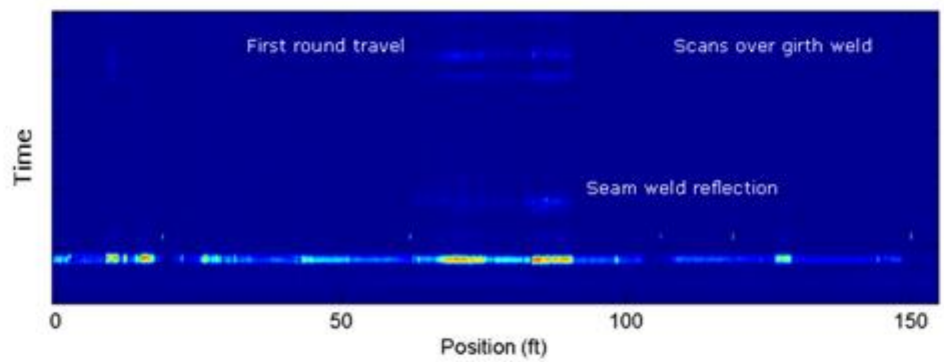

Figure 21: EMAT data sensor travelling over girth welds

By reviewing the data the following observations were made:

1. Regions where the coal tar coating has been removed exhibit a significantly higher direct pulse magnitude than regions where the coating remains. Regions where the coal tar has been removed for the entire circumference show the first round travel double peak.
2. Reflections due to the seam weld can be seen in areas where the coating has been removed. No anomalies were detected in the data in these areas.
3. The girth weld location does not show up directly in the EMAT data where the sensor has been pulled over the welds. Some correlation may be obtained from the attenuation of the direct pulse due to lift off to identify the location of the girth weld.
4. Improvements can be made on the EMAT coil for wear and durability while travelling in the pipe environment, especially over girth welds.

Task 1.3 Revisions of Sensors

Following this first demonstration and in preparation for the second demonstration it was agreed to carry out an operational test of the TMFL/EMAT sensor at the underground test loop owned and operated by NYSEARCH Binghamton, NY on July 30th, 2014, shown in Figure 22. The test loop in Binghamton NY, is an underground section of pipe with various features and defect sets to test various in pipe inspection tools. This test loop was the initial field testing site for Explorer prior to launching in a live pipeline environment. Entry to the 20in portion is above ground at the right of Figure 23. There is a short 40 ft straight section followed by a long radius 90deg elbow. There is 220 ft of straight pipe after the elbow followed by a double S-bend and a plug-valve. After the plug valve there is a mitered bend. There are defects along the length of the test section at undisclosed (to contractors) locations. This test targets the section of pipe between the entry and the S-bend.

Only one section of sensors was installed on the crack sensor module for this test. Furthermore, these sensors were the same type as used on the conventional robot with detection on all three axes (radial, circumferential, and axial). The final sensor elements have only radial sensing due to a requirement for increased sensor spacing.

During assembly, it was discovered that the actuator torque was affected by the magnet fields present on the sensor. While design modifications were underway, the sensor was tested with one (of six) functional magnet bar bank and sensors. Because of this, EMAT data was not collected in this test.

Figure 22: Crack sensor deployed into NYSEARCH underground test loop

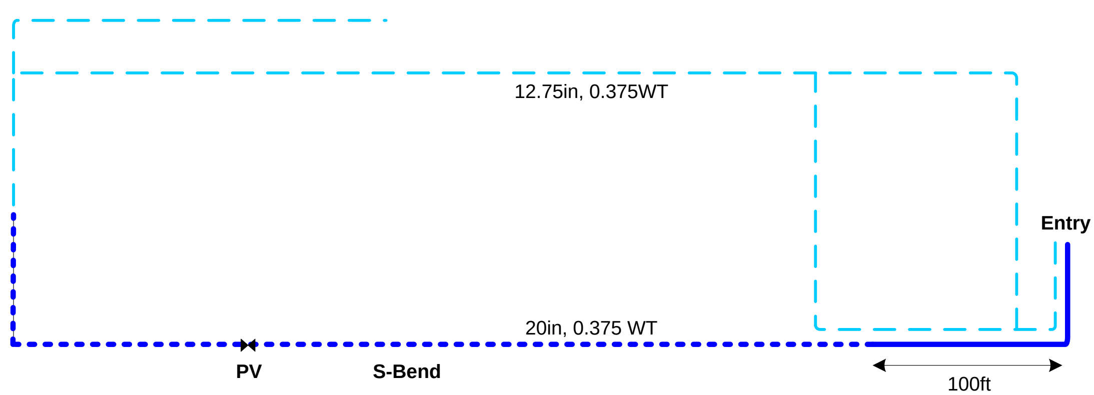

Figure 23: Schematic of test loop. The crack sensor path is shown as a solid line

The robot was driven into the pipe around the first bend and the inspection started. The sensors were monitored during the scan (Figure 24). The robot encountered a dent in the pipe after 100ft of scanning which caused the robot to stop. The sensor could not make it over the dent. Because of communication difficulties retracting the poles was not possible, so the sensor was undeployed and the robot returned to the loop start.

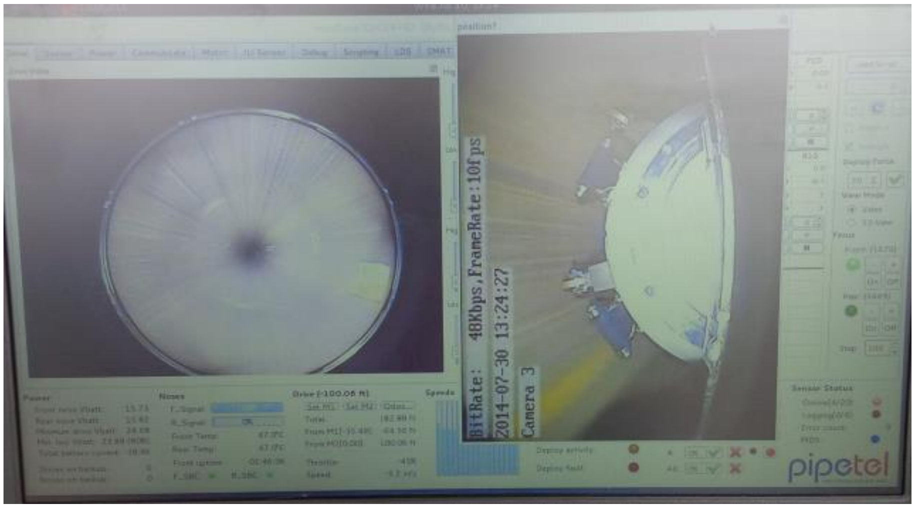

Figure 24: Monitoring sensors during scan

Data collected from this short scan indicated that the crack sensor detected one anomaly (Figure 25). The signature of the defect is consistent with the patterns expected for a defect of this type. Furthermore, the same defect has been measured with the conventional sensing section on other tests.

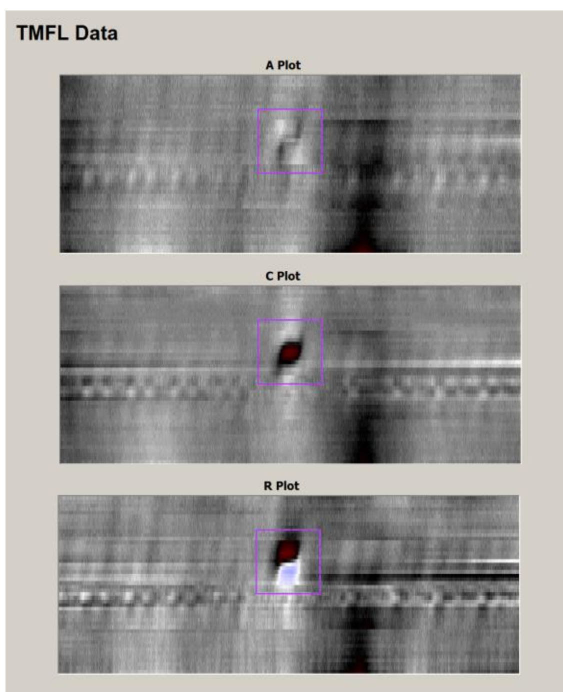

Figure 25: TMFL data of one feature

The mechanical damage sensor measured the height of the dent encountered in the pipe and is visualized via the data viewing software (Figure 26). In addition to the dent measurement, the MDS also shows some of the larger internal pre-machined defects. Previous scans show two defects very close to the girth weld. These defects can be seen in the MDS plot (

Figure 27) meaning that they are on the inside of the pipe. This demonstrates the capability of the MDS system to act as an internal/external defect differentiator.

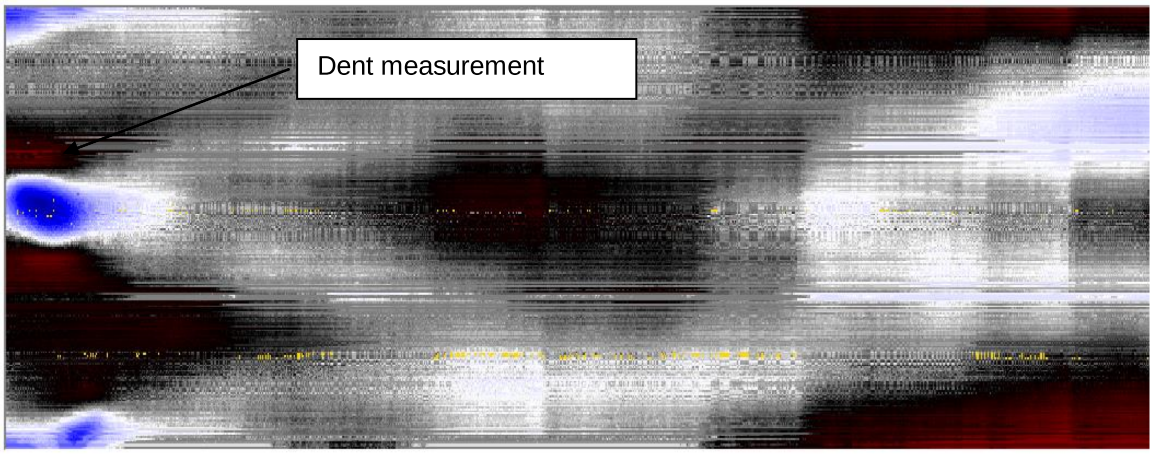

Figure 26: MDS Data from Binghamton showing dent

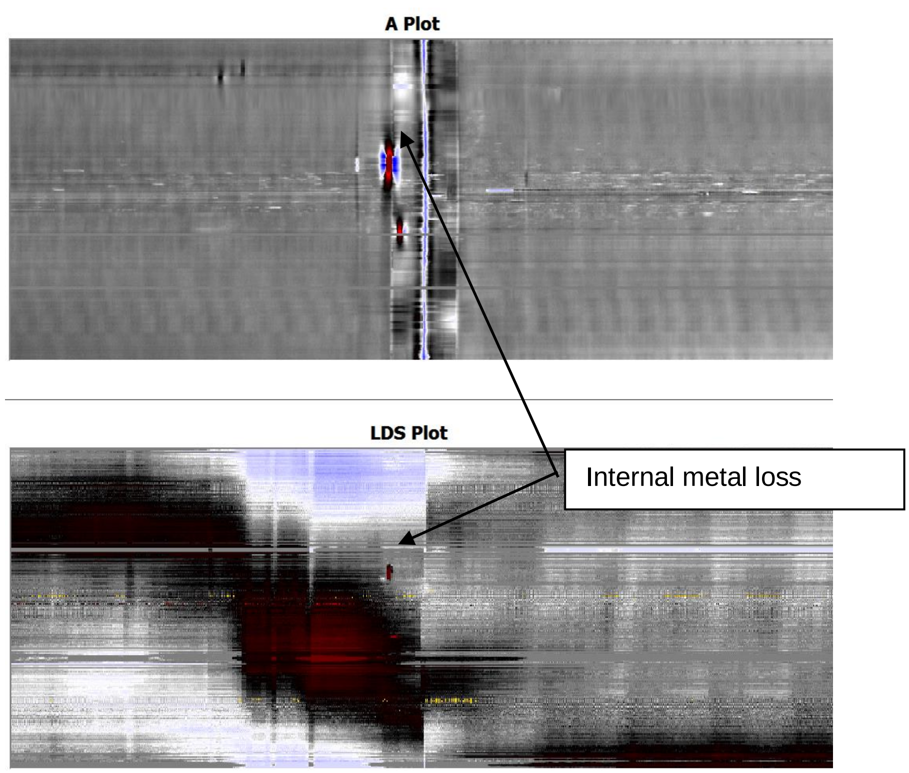

Figure 27: MDS showing internal metal loss features

Following these tests the following changes were made to the system in preparation for live testing:

- The sensing section was shortened. While the overall length of the system remained the same, the overall weight was reduced by 50 lbs. and the actuators were located now in a suitable zone. Because of this change, the actuators could magnetize all of the banks properly.
- TMFL sensor elements were replaced with a lower profile design to satisfy the 75% of pipe diameter requirement when collapsed.
- EMAT pulse and receive components were moved to the interior of the sensor to satisfy the 75% requirement of the system.
- EMAT frequency was changed to better scan with the presence of coating. However, the ability of the system to detect defects in the weld was reduced. This is an ongoing issue with the system.

Task 1.4 Preparation for Second Live Demonstration

The final task prior to the second live demonstration was to pull together the crack sensor system and mechanical damage system to operate in a live pipeline. The objective of the second demonstration was to collect TMFL, EMAT, and MDS data in a live pipeline and report on any defects detected. This test was targeted to occur in September of 2014 in a mountain state, following a commercial deployment of the Explorer 20/26 tool. The Invodane team installed the crack sensor onto the Explorer robot. During preparation, feedback regarding the pipeline conditions was received from the commercial inspection run of Explorer. The team carrying out the inspection noticed very slippery conditions during exit from the pipeline. Based on available information on robot capabilities and pipeline conditions it was deemed that the risk of carrying out the test was too high. Thus, the demonstration was canceled the evening before the planned demonstration.

Despite the cancelled run, the robot was driven into the already installed launcher and underwent testing involving the functions required to carry out an inspection. The robot was function tested up to 340 psig with all components operating as expected

Error! Not a valid bookmark self-reference.). In this function test, the sensor was deployed to the pipe wall, the sensors were turned on, and data was recorded with the stationary robot. After all checks were completed, the sensor was collapsed and the unit was taken out of the launcher. No damage was observed on the system as a result of pressure.

Task 1.5 Second Live Demonstration

Following the cancellation of this demonstration, NYSEARCH staff initiated an immediate search to identify an alternate location. A new location was secured in the west coast and the second demonstration was carried out under live conditions on November 14, 2014, in a 20 in pipeline with a wall thickness of 0.312in. The sensor was installed onto the robot and function tests performed (Figure 29). The system was deployed into the pipeline (Figure 30) where large amounts of debris were encountered. The debris can be seen in Figure 31 with accumulated section near the hot tap entry point.

Figure 29: Setup of crack and MDS sensor for west coast demonstration

Figure 30: Crack and MDS sensor on Explorer prior to launch

Figure 31: Views of debris from different positions near the hot tap

The scan profile is shown in

Figure 32. After the robot was fully entered into the pipeline, it travelled approximately 10 ft until the debris field was reduced. The sensor was deployed to the pipe wall with both EMAT and TMFL systems indicating good signals. Scanning was started at a speed of 2in/s. The robot travelled approximately 30 ft into the pipe when the first girth weld was seen. A large amount of debris was observed across the girth weld. It was decided to terminate the inspection with the data collected thus far. The robot was driven out of the pipe without incident and the data was downloaded for analysis.

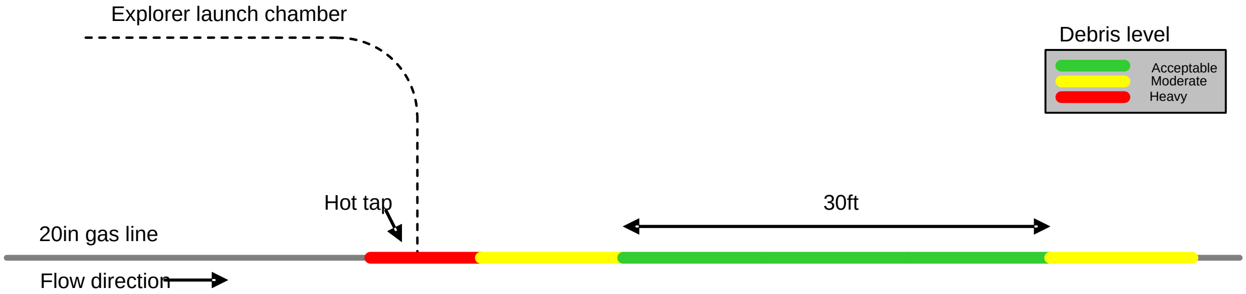

Figure 32: Debris levels in live test pipe for crack sensor

Analysis of the data shown in

Figure 33 indicated the following:

1) The seam weld can be identified in the TMFL data. However, no known anomalies existed and no anomalies were recorded on the seam weld.

2) MDS data shows the profile of the debris in the pipe, especially in the high debris areas. The MDS system is on the rear of the robot which entered the pipe first so the large pile of debris was not measured. However, the debris on each side of the robot path were observed (and is shown in Figure 34).

3) An error on the EMAT data synchronization pulse meant that the strong signal recorded in the pipe was a result of noise between the transmitters and receivers. The effect and failure mode of this had not been encountered before and will be investigated moving forward.

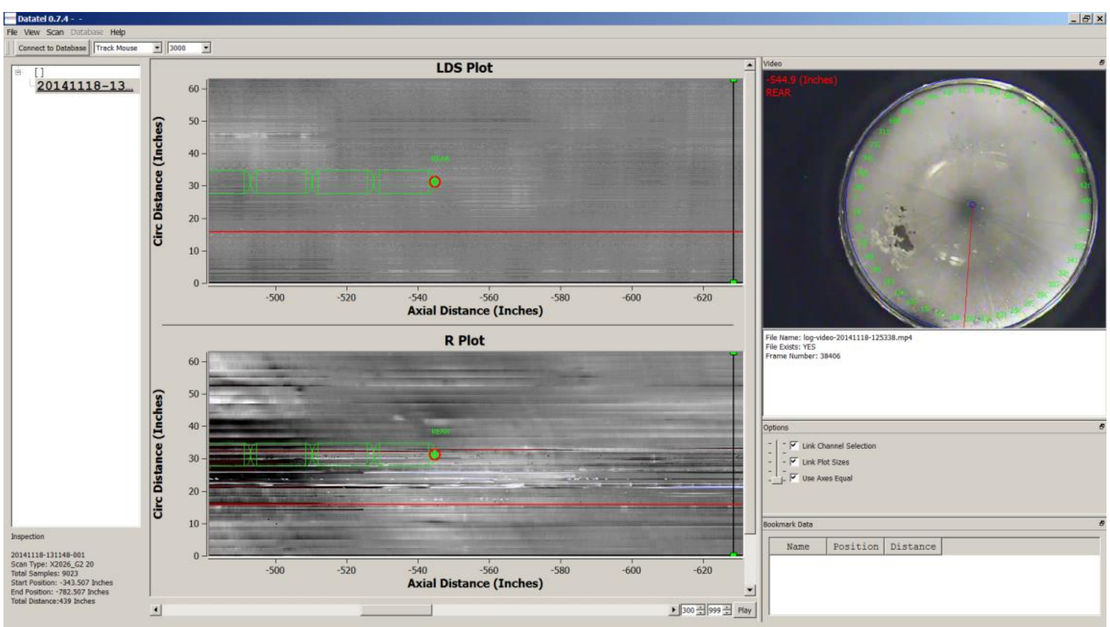

Figure 33: TMFL and MDS data from west coast run

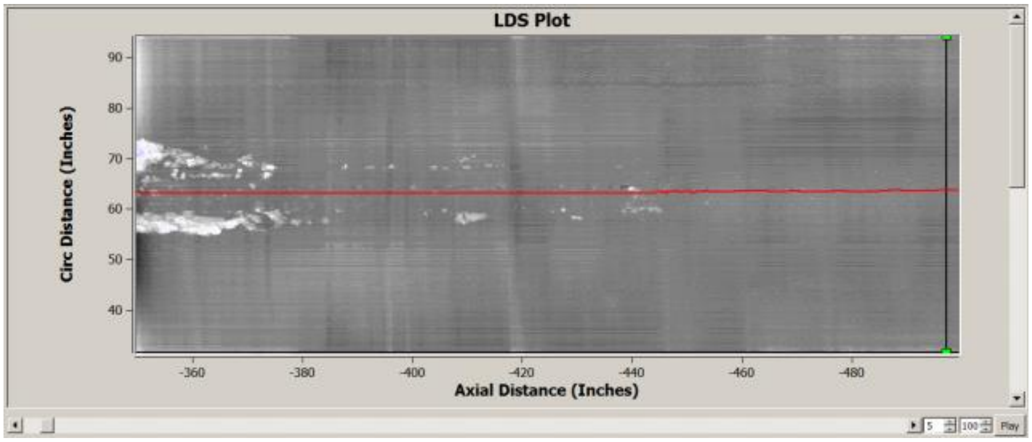

Figure 34: MDS data from west coast run showing debris

Task 1.6 Revision of Sensors

Following the results of the first two demonstrations and given the experience gained, we implemented changes to: (a) reduce the length of the sensor, (b) improve the sensor actuation system and (c) improve the overall reliability of the system for operational use. Work on sensor improvements was completed prior to the third field deployment with final modifications to the EMAT probe configuration implemented following the third field demonstration.

The length of the sensor gave us marginal abilities to negotiate mitered bends and other features, and its reduction was imperative in allowing for more reliable and efficient operation. Through changes implemented in the gearbox, which resulted from changes to also improve the reliability and efficiency of sensor deployment, the length of the sensor module was reduced by a small amount, which was however a relatively large reduction resulting in the improvements desired.

Another change implemented was improving the margin of safety on the pole actuation force. Through this redesign the actuation force has increased more than three times (300%) and the speed of actuation has increased as well (by 14%). Again, the reduction in length provides better maneuverability within the pipeline, especially during entry and exit from the pipe through a hot tap. New electronics provide increased signal to noise ratio, thus improving defect detectability.

All these changes were implemented on the sensor. The sensor module was reassembled and tested before been integrated to the Explorer 20/26 sensor. The integrated sensor/platform system was successfully tested in the lab and was now ready for its next field deployment.

Task 1.7 Preparation for Third Live Demonstration

Given the many changes in sensor design and the difficulties in identifying a site for a third live field demonstration within reasonable time limits, approval was sought from and given by PHMSA's project manager to carry out the third field demonstration at the NYSEARCH Test Bed, where we would have the freedom for extensive testing of the system without the pressures and difficulties imposed by working under live conditions. Thus, the third field deployment of the crack sensor was planned for the NYSEARCH Test Bed in Johnson City, NY. The sensor would be deployed in a 20" line and negotiate a short radius 90-degree bend followed by back to back 45-degree bends. The walls of the pipe have a number of defects on them which would allow us to test the capabilities of the sensor.

Task 1.8 Third Live Demonstration

The third field deployment of the crack sensor took place in the NYSEARCH Test Bed in Johnson City, NY, on October 5-6, 2015. The sensor was deployed in the 20" segment of the piping network (with a wall thickness of 0.250") and inspected part of that segment, from the inlet point to the point where there is a plug valve. During the first day the crack sensor and robotic platform systems were checked for proper operation and the network was prepared to receive the system. During the second day the robot was launched into the pipe from an open end (Figure 35) and proceeded to inspect the pipe. The inspection was successful in that the robot was able to negotiate all features without any problem and the TML and EMAT sensors collected a full set of data.

Figure 35: Robot with crack sensor prior to launching

Sample results from the TMFL sensor are shown in Figure 36, while results from the EMAT sensor are shown in Figure 37. The seam weld is clearly visible in both sets of data. The TMFL data also show the defects that are built onto the pipe.

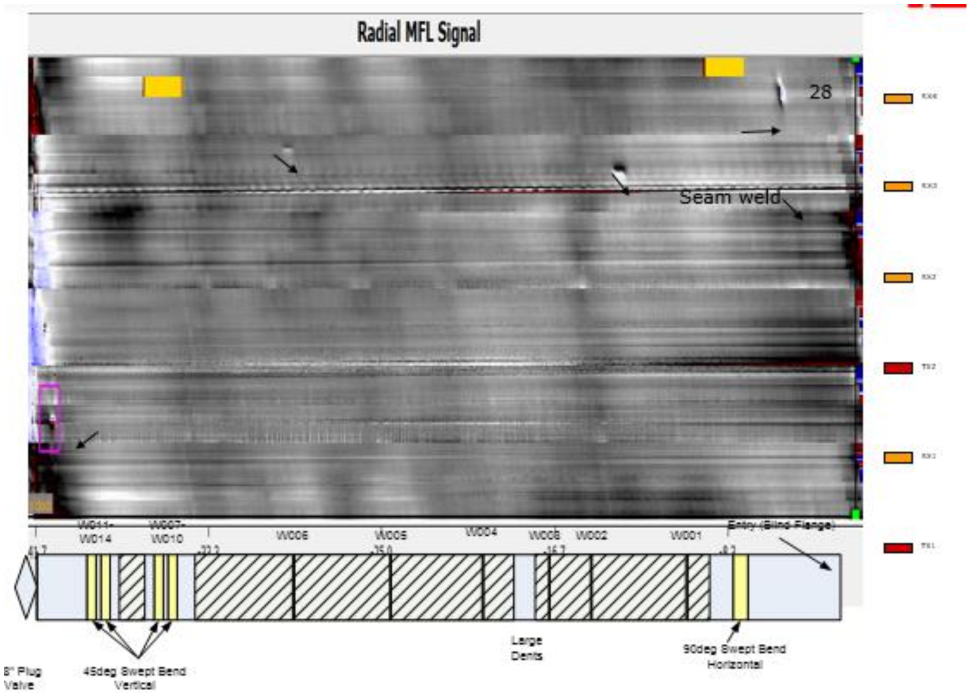

Figure 36: Data analysis results for TMFL sensor

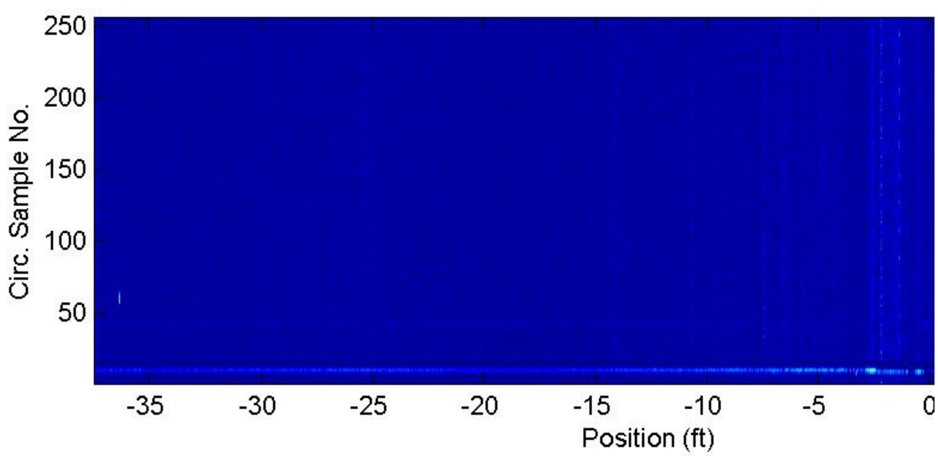

Figure 37: Data analysis results from EMAT sensor

Task 1.9 Revisions of Sensors

With the successful testing of the sensors at the NYSEARCH Test Bed, the redesigned sensor was fine-tuned and minor changes implemented in preparation for the fourth and last field demonstration. All mechanical parts were checked for integrity and final implementation for the protective materials for the sensor elements was carried out.

Task 1.10 Preparation for Fourth Live Demonstration

In continuous discussions with a western company we were able to secure a field demonstration for the crack sensor that would follow a commercial inspection of the pipeline by Pipetel Technologies. Weekly calls among the host company, Invodane/Pipetel and NYSEARCH were initiated in September 2015 to coordinate the entire effort. The target commercial date was set for October 28, 2025. At the end of that inspection the axial MFL sensor would be removed and replaced with the crack sensor. The next day, October 29, 2015, the crack sensor demonstration would take place. On October 26, when the site was excavated in order to weld on the access fitting, a defect was found on the pipe. This required the immediate repair of the pipe thus, causing a delay in the commercial deployment and the demonstration. Through daily interactions we were able to reschedule the inspection date and demonstration date for November 4 and November 5 respectively. Repairs were carried out on time and we were able to carry the two deployments as per revised schedule.

Task 1.11 Fourth Live Demonstration

The fourth and last field demonstration of the crack sensor was carried out on November 5, 2015. The objective of this deployment was to inspect a live pipeline using the redesigned (current implementation) of the Explorer's new crack sensing module. The test site is shown in Figure 38. The pipeline was 20 in OD with 0.344 in wall thickness, with an operating pressure typically in the 250-345 psig range. The day of the test the operating pressure was 215 psig.

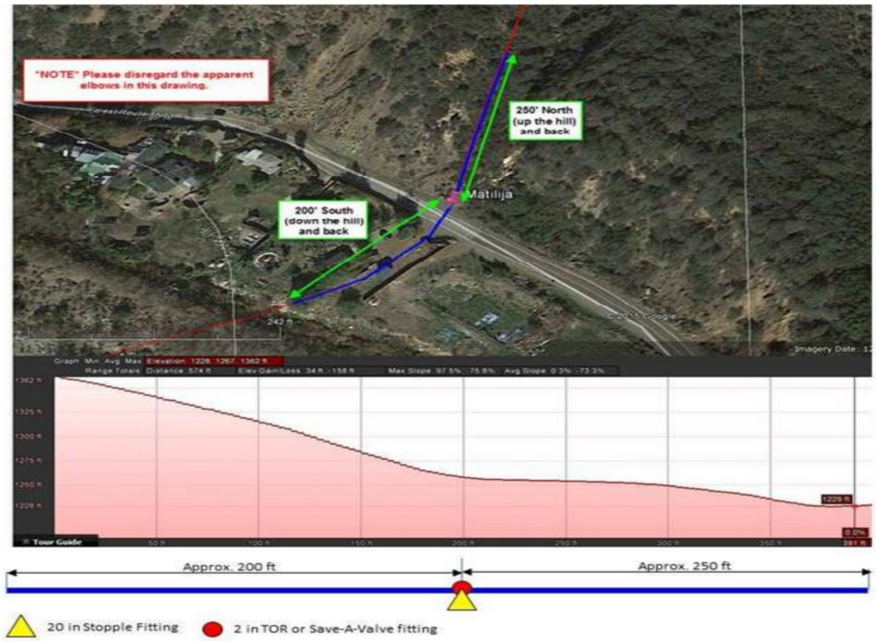

Figure 38: Site and pipeline configuration of fourth demonstration site

Operational procedures call for the launcher to be installed parallel to the pipeline. This ensures the efficient and reliable launching of the robot into the pipeline. However, in this case installing the launcher this way would completely block traffic on the road. It was decided to install the launcher at an angle of 15-deg to the pipeline, an angle that would keep one lane open and would minimize the impact on the launching routine (Figure 39). As mentioned above, repairs were made on the pipeline prior to the deployment, which can be seen in Figure 40.

Figure 39: Installation of launcher at fourth demonstration site

Figure 40: Excavation showing the repairs made to the pipeline and the base of the valve/launcher installation

The robot with the crack sensor was launched in the pipeline of November 5 and inspected a length of about 200 ft. All operations were carried out with no problems with the exception of one of the EMAT sensor elements that was damaged towards the end of the inspection. It needs to be mentioned that the pipeline was full of liquid/solid debris and that may have contributed to the damage of one of the EMAT receivers.

Data was collected from the pipeline from approximately 8.5 ft from the hot tap for approximately 200 ft and again on return. The sensor was rotated 180 deg for the return scan. An example of data from the demo is shown in the following figures. Figure shows the magnetic flux levels represented as a surface plot. A typical view of the long seam weld is shown as well as the bottom of the pipe location (shown in red). For both sets of data (scanning away and towards the hot tap), there were no indications detected in the seam weld that would indicate the presence of cracks.

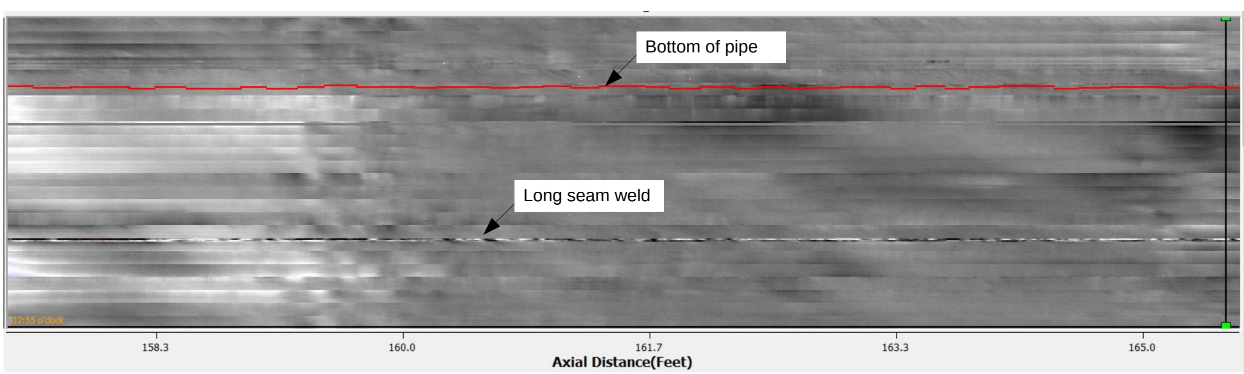

Figure 41: Data from fourth demonstration showing pipeline's long seam weld

Figure 42 shows the data in the vicinity of a girth weld. The girth weld is easily identifiable across all channels. In most cases, the sensor needed to be slightly collapsed to traverse the girth welds. The data shows changes in the overall magnetic signature before and after the girth weld.

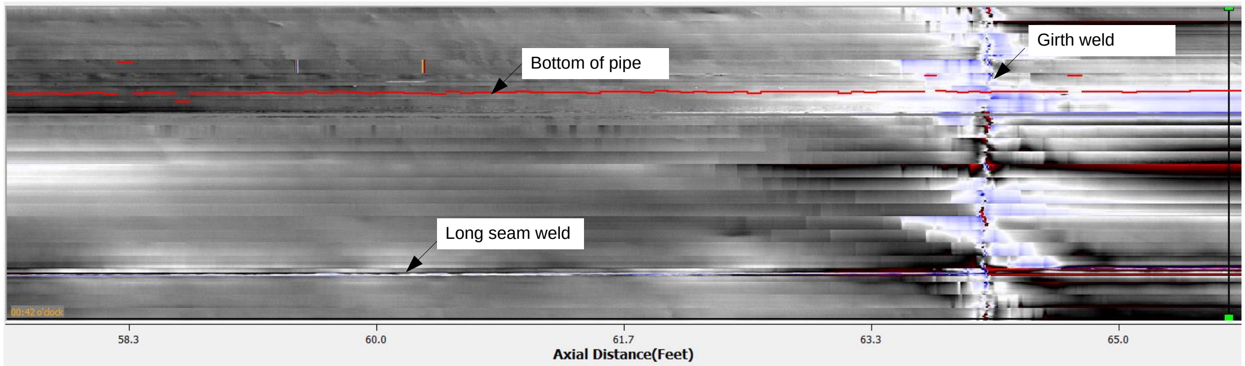

Figure 42: Data from fourth demonstration showing girth weld

EMAT data showed an improved but limited response from prior inspection results. For this demonstration, the EMAT sensors were run at a lower frequency in order to minimize the dampening effect of the pipe coating. Based on laboratory results, it was expected that there would be a tradeoff in sensitivity to surface features in the pipeline. The EMAT sensors were recorded to travel the full circumference of the pipe, however the weld is barely visible as seen in Figure 43. There were also some instances of EMAT sensors becoming detached from the pipe wall during scanning, especially for sensors located at the top of the pipe. In the EMAT data this is indicated by the absence of both the direct peak and the round trip pulse (shown in Figure).

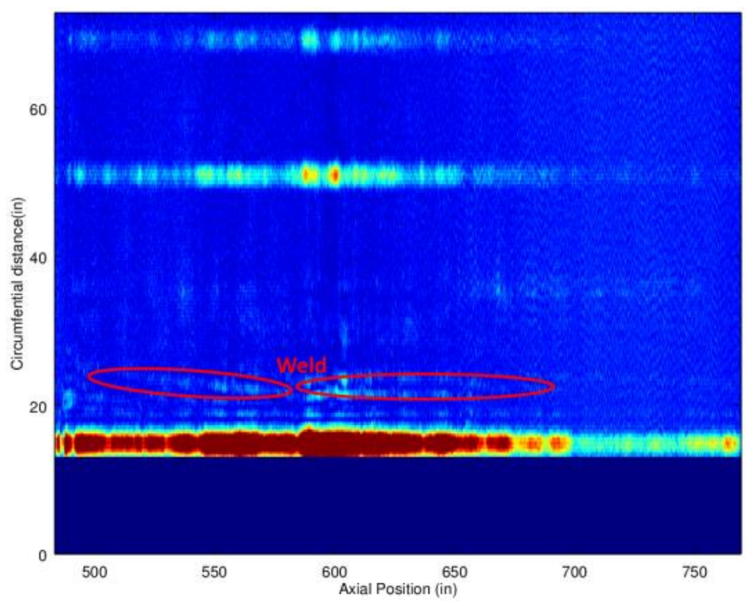

Figure 43: Sample EMAT data from fourth demonstration

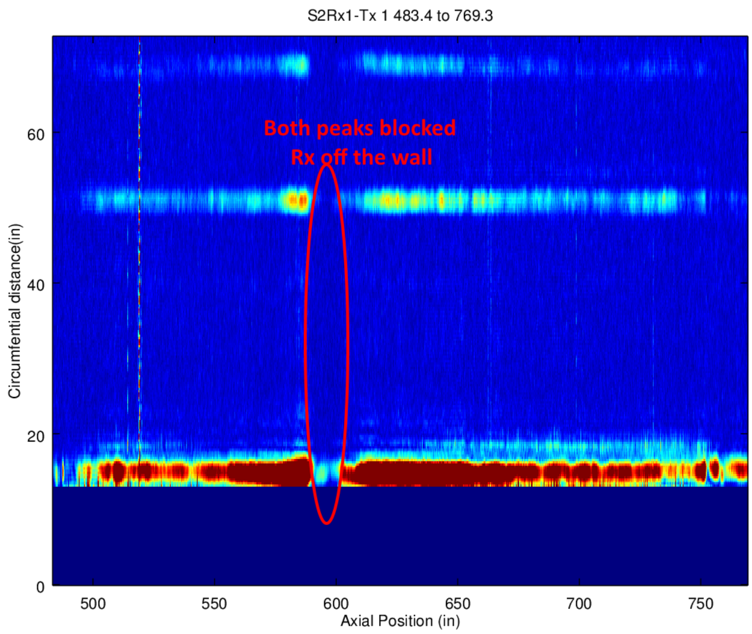

Figure 44: EMAT receiver lift off; fourth demonstration

Task 1.12 Commercialization

Following the completion of the field demonstration program, the crack sensor was prepared for commercial deployment. The data processing and defect sizing software was integrated into the Explorer data analysis package. Last upgrades to sensitive components (damaged during the last deployment) were made. The crack sensor is now available for commercial deployment through Pipetel Technologies Ltd., the company that provides inspection services to the gas industry for unpiggable natural gas pipelines using the Explorer family of platforms and suite of sensors.

The mechanical damage and ovality sensor has now been commercialized and is available not only on the Explorer 20/26 but also on all other Explore platforms (Explorer 6/8, Explorer 10/14, Explorer 16/16, and Explorer 30/36). The data processing and dent sizing software was integrated into the Explorer data analysis package. The mechanical damage sensor is thus now commercially available through Pipetel Technologies Ltd., the company that provides inspection services to the gas industry for unpiggable natural gas pipelines using the Explorer family of platforms and suite of sensors.

CONCLUSIONS

Two new sensors have been tested and commercialized through this research effort cofounded by NYSEARCH and PHMSA that will great enhance our ability to inspect unpiggable natural gas pipelines and improve the safety of the natural gas infrastructure. These two sensors add to the existing capabilities of the Explorer robots, which now offer the same sensing capabilities as traditional smart pigs.

FUTURE WORK

As technology involves rapidly making available new improved systems, further enhancements are possible and will be implemented in the future. A number of modifications are already looked upon and will be implemented in the future. These modifications include:

TMFL Sensor packs
The current sensor packs measure only the radial direction component of the magnetic flux vector. Since the crack sensor was designed, newer sensors have been made available that may allow sensing all three components (radial, circumferential, and axial) of the magnetic flux vector. These sensors will need to be packaged according to the denser spacing aboard the crack sensor elements. Sensor element positioning and robustness will be revisited with replacement of these hall sensors on the module.

EMAT Sensors
EMAT use aboard the crack sensor has been demonstrated in a laboratory environment to be capable of crack detection for uncoated pipe. For the EMAT system to be effective aboard the crack sensor, the distance that the reflected pulse travels needs to be minimized. Since the crack sensor has very distinct locations where the EMAT receivers and transmitters can be mounted, the first step is to develop the sensing technology to allow the transmitter and receiver units to be placed in the same location.

Real crack samples
InvoDane currently has a large inventory of sample defects for metal loss and is building its collection of pipes with simulated cracks of different depths, lengths, and positions within the pipe circumference. As with all sensors on the Explorer robots, Invodane is continually building its collection of crack-like defect samples and data processing capabilities to properly identify and size different types of cracks. NYSEARCH and Invodane continue searching for opportunities to obtain samples of naturally formed cracks to compare against the simulated crack samples used in this program to perform data analysis.

Sensor overlap handling
There are sensors aboard the crack sensor module that overlap each other. Currently only one set of data is processed from these overlapping sensors. The additional data may be able to be used to provide information to the operator on the quality of the data being collected. This is an area of further research that can be performed after initiation of commercialization.